Optimization of Image Quality and Dose in Digital Mammography

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Abstract Nowadays, the optimization in digital mammography is one of the most important challenges in diagnostic radiology. The new digital technology has introduced additional elements to be considered in this scenario. A major goal of mammography is related to the detection of structures on the order of micrometers (μm) and the need to distinguish the different types of tissues, with very close density values. The diagnosis in mammography faces the difficulty that the breast tissues and pathological findings have very close linear attenuation coefficients within the energy range used in mammography. The aim of this study was to develop a methodology for optimizing exposure parameters of digital mammography based on a new Figure of Merit: $\text{FOM} \equiv (\text{IQF}_{\text{inv}})^2 / \text{AGD}$, considering the image quality and dose. The study was conducted using the digital mammography Senographe DS/GE, and CDMAM and TORMAM phantoms. The characterization of clinical practice, carried out in the mammography system under study, was performed considering different breast thicknesses, the technical parameters of exposure, and processing options of images used by the equipment's automatic

exposure system. The results showed a difference between the values of the optimized parameters and those ones chosen by the automatic system of the mammography unit, specifically for small breast. The optimized exposure parameters showed better results than those obtained by the automatic system of the mammography, for the image quality parameters and its impact on detection of breast structures when analyzed by radiologists.

Keywords Digital mammography · Image quality · Contrast-detail analysis · Figure of merit · Optimization · CDMAM · TORMAM

Introduction

To detect breast cancer early, mammographic images should exhibit a high contrast, which is not an easy task since the parts that compose the breast have similar radiation attenuation coefficients. In addition, the spatial resolution must be able to show the microcalcifications, their number, and their shape. Image noise level has to be low enough to reveal the breast structures in a reliable way. Although the system image features are primary factors, when the mammography unit characteristics are good enough, the optimization process can significantly enhance the attainment of high quality mammograms. The optimization of the mammography system involves the best performance of image quality parameters with the radiological dose as low as possible, reaching the radiological goal which is the best diagnostic [1, 2].

The introduction of new technologies in mammography can lead to improvements in image quality; however, it can unnecessarily increase the doses if optimization procedures are not applied. Several studies show that, even after optimization, new technologies can provide higher doses [3–6].

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Thus, studies of each technology are required when there is technological transition, in order to maintain image quality without a significant increase in doses to the patient [7].

In the evaluation of image quality, the physical methods include contrast measure, noise, spatial resolution, modulation transfer function (MTF) [7, 8], detective quantum efficiency (DQE) [7, 9, 10], and others. These metrics are reproducible and allow a direct comparison of performance between different imaging systems or techniques.

A general improvement in the mammographic service indicators is expected with the development of new digital technologies. However, certain questions remain open that are reflected directly in the accuracy of clinical diagnosis. One of the current problems, pointed out by several authors, is that the comparison of the accuracy of the diagnosis between the screen-film and digital systems does not show significant differences in the detection of nodules, calcifications, and asymmetries in the breast [11–15]. Another issue widely discussed in literature refers to the burden of false positives and false negatives still present in mammography diagnostics [16–22]. Several papers discuss their psychosocial and economic consequences pointing, in most cases, to several subjective causes present in the screenings [23–25]. On the other hand, this fact is also a good indication for the need of the improvement of the optimization methods for the existing technology. The metrics used in optimization procedures such as SNR, CNR, MTF, and DQE are applied to raw images. However, images that are evaluated directly by radiologists are from the processed type. Nowadays the influence that the image format (raw or processed) can have in the optimization of mammographic system is an open question [26].

One of the image quality assessment methods, considering the observer, includes studies that use contrast-detail phantoms (CD). The use of these test objects by a group of observers allows to compare the performance of different image systems in a way that includes the variability of human perception. Therefore, their results can be used for making a decision regarding the application of a new technology [27]. In the work of Fletcher-Heath and Van Metter [28], a detailed contrast-detail analysis of the CDMAM phantom's images is shown, using the software and comparing with the human observers performance. The results of this study show a large inter-observer variability and highlight over the long and tedious period of time that is necessary for human scoring, indicating the desirability to qualify a readily available software solution. In this work, we have used this approach.

Many studies indicate that it is possible to reduce the radiation dose without loss of image quality [3, 4, 29]. According to Borg et al. [26], the use of Figure of Merit (FOM) is a very practical way to perform the optimization process. The FOM is an evolving quality indicator and is presented as a single number that reflects the status or the performance of any specific system under certain conditions. There are several FOM

definitions used for optimization in digital mammography [3, 30–33].

Others studies have focused on characterizing the performance of the detector, using the modulation transfer function (MTF) and the detective quantum efficiency (DQE) [26]. However, these metrics are very limited for use as a global indicator for image quality [34].

The aim of this work is to develop a new integrated optimization methodology for radiological procedures used in the clinical practice of mammography. In this regard, the proposal for a new FOM, its application in the optimization of equipment should be considered, taking into account the performance of physical parameters of the image and the efficiency in the identification of the breast structures by radiologists.

Materials and Methods

This study was conducted using the mammography unit of General Electric (GE), Senographe DS model, installed in the radiology department of the Instituto Português de Oncologia de Coimbra (IPOC). During the investigation, the conformity of the equipment was verified with the achievement of quality control tests recommended by the manufacturer [35] and the basic tests suggested by the European Guidelines [36]. In addition, at the beginning and end of each measurement, an image quality study was carried out using the ACR phantom, where the following parameters were analyzed: signal to noise ratio (SNR), contrast to noise ratio (CNR), and the visualization of microcalcifications, filaments, and masses.

The used methodology was developed in three stages. The first entailed the characterization of the typical breast thickness ranges found in the IPOC and the exposure parameters selected by the automatic system of the equipment. The second stage included the study of optimization of the mammography exposure parameters. We defined a new FOM. The variation in the exposure parameters was measured by using the contrast-detail phantom and the ionization chamber. From these measurements, the optimal points were found by using the FOM. The third stage consisted in studying the impact of the optimization in the capability of detecting breast structures. With the use of anthropomorphic phantom, three types of images were generated using different values of the exposure parameters to be compared between them, as detailed in the subsection “[Study of the Optimization Impact in the Detection Capability of Breast Structures.](#)”

Characterization of Typical Breast Thickness Ranges

A representative sample of the examinations performed at the IPOC was randomly selected between 2009 and 2010, in order to characterize and classify the typical breast thicknesses in

the patients. The selected information, which constituted our database, was obtained directly from each image stored in the Digital Imaging and Communications in Medicine protocol (DICOM). The database is composed by the following information: the exam date; age of the patient; view of examination; operation mode of the automatic exposure control (AEC); the technical parameters of exposure (target/filter combination (T/F), kVp, and mAs); the thickness of the compressed breast (E); the applied compressive force (F); the glandular percentage; the entrance skin exposure (ESE); and the average glandular dose (AGD) as registered by the equipment. The average values of the numerical variables were compared by type of view, using Student's t test for independent samples.

In this study, a sufficiently large sample was chosen to properly characterize the types of breast and the average exposure parameters found for the institution. In order to obtain a representative sample, different days of the week were randomly selected within a period of 4 months. In these specific days, all mammograms that had been carried out were collected. Thus, a statistically representative sample corresponding to 10 % of all exams performed annually in the IPOC was considered to determine three breasts sizes, each corresponding to a specific thickness range. The points used as lower/upper confidence limits for these ranges were established from the average breast thickness of the entire sample $\pm$ the standard deviation (SD) with 95 % of confidence level. Three types of breasts were defined: small (S), medium (M), and large (L) for which the defined ranges of breast thicknesses were as follows: $E_S < 45$ mm; $45 \text{ mm} \leq E_M < 70$ mm; $E_L \geq 70$ mm.

The validity of this proposal was verified by means of analyzing the existence of statistically significant differences in the set of variables used in each group: types of view, target/filter, kVp, mAs, compression strength, and exposure. The association of categorical variables with the defined intervals was evaluated using the coefficient of V Cramér, and for the case of quantitative variables, we have used Student's t test for independent samples with Bonferroni's correction [37].

Optimization Study of Mammography Exposure Parameters

From the three defined intervals of compressed breast thicknesses (E_S , E_M , and E_L), a typical thickness of the compressed breast was chosen for each group (E_{S_t} , E_{M_t} , and E_{L_t}). The typical thickness in each interval was selected in accordance to various criteria. Initially, the thickness values were selected from those whose physical parameters of exposure (target/filter, kVp, and mAs) occurred more often within this thicknesses range. In this subgroup of possible values, the thickness was chosen around the average thickness identified for the corresponding range, which could be obtained using the

combination of the available PMMA plates (5 and 10 mm).

To optimize the image acquisition process, we have chosen to evaluate image quality using the inverted Image Quality Function (IQF_{inv}) parameter that expresses the detection threshold of an imaging system in relation to the background of the image, according to their contrast and object sizes (contrast-detail curve). We have used the Contrast-Detail Mammography Phantom (CDMAM, type 3.4) [38] to obtain the images.

The CDMAM Phantom consists of an aluminum base with gold disks, which is attached to a Plexiglas cover. The phantom has a matrix of square cells, 16 columns and 16 rows, with disks of varying diameter (from 0.06 to 2.00 mm) and thickness (from 0.03 to 2.00 μ m). Each square contains two identical disks, one in the center and one in a randomly chosen corner. The detection of disks by the observer is evaluated as percentages of correct detections per image.

The IQF_{inv} was obtained using the test object CDMAM (Contrast-Detail Mammography), which determines the contrast (thickness) threshold in the image of the object as a function of the detail (diameter) according to:

$$IQF_{inv} = \frac{100}{\sum_{i=1}^{16} c_i^{th} \cdot D_i} \quad (1)$$

Where C_i^{th} denotes the thickness detection threshold in the D_i diameter-column i .

The CDMAM allowed us to obtain the system's contrast-detail curve to determine the visibility threshold. This curve is associated with the detection capability of the smaller structures, depending on the technical parameters of the image-obtaining process. A quantitative and objective evaluation of the images obtained using the CDMAM 3.4 was performed. To calculate the IQF_{inv} , in each case, we have used the CDMAM Analyser software version 1.2 [39].

Once the conditions were set: breast thickness, the T/F set, and the applied voltage to the bulb, the value of IQF_{inv} increases with the mAs. Thus, it was necessary to define a clear criterion for determining current-time products in order to obtain images and IQF_{inv} values that would be comparable. We have used the criterion suggested by Ranger, Lo, and Samei [3], which consists in using the current-time products that supply an average value for the image's pixel number close to the value recommended by the manufacturer. For the Senographe DS mammography system, the average value of the recommended number is 900 pixels in accordance with the National Health Service Breast Screening Programme—NHSBSP [40]. All the images obtained with the CDMAM Phantom had the current-time product (mAs) selected so that the average pixel value was 900 ± 10 %. The number of pixels was measured on CDMAM in a region of interest (ROI) of 400 mm² without gold structures.

The FOM proposed herein is calculated from IQF_{inv} according to the following equation:

$$FOM = \frac{IQF_{inv}^2}{AGD} 10^{-6} [\mu m^{-4}] [mGy^{-1}]. \quad (2)$$

The AGD was calculated from the entrance air kerma measurement in the detecting surface without backscatter, according to:

$$AGD = g_t c_t s K_{a,i} [Gy] \quad (3)$$

Where:

- $K_{a,i}$ is the entrance air kerma at the surface measured without backscatter
- s is the correction factor that depends on the target/filter combination
- c_t is the conversion factor to correct the difference in the breast composition from 50 % glandularity [mm]
- g_t is the factor that converts the $K_{a,i}$ in AGD for a breast with 50 % of glandular tissue.

The measure of $K_{a,i}$ was performed according to the methodology proposed in the European Protocol on Dosimetry in Mammography [41], using the dosimetry set composed by the 9095 model Radcal electrometer coupled to the ionization chamber (IC) dedicated to mammography 10x9-6M model. The AGD calculation was performed using the formula proposed in the European Guidelines [36] and by the International Atomic Energy Agency [2].

The values used for s , c_t , and g_t were taken from [42] in accordance with the corresponding age range.

For each typical compressed breast thickness, a target/filter combination used in clinical practice was selected and the IQF_{inv} was obtained for the entire voltage range (kVp) allowed by the equipment. The Gaussian function supplied the best fit for the FOM versus kVp curves. For each studied target/filter combination, the optimum voltage applied to the X-ray tube was determined from the maximum of the FOM versus kVp curve.

In a second step, the optimization for the current-time product was performed. For each T/F combination, a curve of FOM versus mAs was obtained using the optimal kVp value. The mAs values varied along the range allowed by the equipment at the fixed conditions: breast thickness, T/F combination, and optimal kVp.

The A-type uncertainties were associated to the results of IQF_{inv} and $K_{a,i}$. The B-type uncertainty was originated directly from the calibration certificate of the ionization chamber. The uncertainty associated to FOM, which is shown in the results, comes from the propagation of uncertainties of IQF_{inv} and AGD.

Study of the Optimization Impact in the Detection Capability of Breast Structures

In order to evaluate the validity of the assessment performed with the CDMAM test object, the TORMAM phantom was used [43, 44] which is recommended as an acceptable alternative to check the image quality in NHSBSP [40]. The images obtained from TORMAM using the parameters optimized by the FOM were compared to images generated from other sets of physical parameters. The first image was obtained from the optimized parameters; the second one with the exhibition automatic system of the equipment in the standard mode (STD); and the other using the kVp and mAs parameters corresponding to the maximum value of the FOM for the Mo/Mo combination of T/F. The quality of the images was compared based on other physical metrics such as the signal-to-noise ratio and number of gray levels. A comparative study was also carried out based on the detection level of the breast structures from the radiologists' assessment, using the TORMAM phantom images.

The TORMAM phantom images were presented to six radiologists with more than 5 years of practical experience in mammography readings. Each image was evaluated by the same radiologist in three different positions, namely the sector of TORMAM structures was presented at the 1st, 3rd, and 4th screen quadrants. The radiologist's clinical routine monitor, a Cathode Ray Tube type (CRT)-Hewlett-Packard (HP)-5 MP was used. The quality control procedures of European guidelines [36] including all the monitor's tests such as luminance measures, geometrical distortion, contrast visibility, resolution display artefacts, Grayscale Display Function, and lighting conditions in the reading room were performed throughout the duration of the project. All parameters remained within the recommended standard values.

The images were shown to the radiologist that was not informed about the parameters defined for the exposure. The radiologist attributed a score to each identified structure, according to the degree of visibility that each structure could be detected, i.e., 1—visibility threshold; 2—visible; 3—clearly visible. The sum of the scores assigned to each structure in each image was defined as the *Visualization Indicator*.

The data set of the visualization indicators was analyzed with statistical methods. The inter-observer variability was assessed between the measurements of radiologists for each set exposure parameter and each breast structure, using the variance analysis with random effect. The analysis of the fluctuations of the measurements from the same radiologist (intra-observer variability) was performed using the intraclass correlation coefficient (ICC). This coefficient ranges from -1 to 1, so that the closer it is to 1, the smaller the intra-observer variability will be. The average values of the evaluations of radiologists were compared by linear mixed model, aiming to establish the set exposure parameters of the mammographic

system that provided better visibility of the structures (microcalcifications, filaments, and mass). In both methods, the analysis of variance with random effect and the linear mixed model have shown normality assumptions in the data distribution, which was verified using the Kolmogorov-Smirnov test [45].

Results and Discussion

Characterization of Breast Thickness

From the set of examinations carried out per year in the radiology service, 10 % of total were selected, which corresponds to 2441 clinical images that have been included in the database. It was found that 95 % of the images in the database were obtained using the STD automatic mode exposure of the equipment. The number of images registered in the database of patients with less than 40 years of age was 176, representing 7 % of the total, and 725 images of patients with ages over 64 representing 30 %. In other words, 63 % of the total of the images are of the patients with ages in the range 40 to 64. The proportion of women aged 40 to 64 years was 62 %, and the subgroup aged 50–64 years was 42 %. The group of women aged under 40 years was 6 %, and 32 % for those older than 64. The difference between the percentages of images and patients in each age interval is around 1 %, because not all patients contribute individually with the same number of images.

The distribution of the compressed breast thickness can be seen in Fig. 1. The obtained average thickness ($\bar{E}$) and standard deviation (SD) is (57.7 ± 13.1) mm.

The thickness ranges were determined considering all the images acquired by the AOP operating system in STD mode only, which corresponds to 95 % of the total number of images acquired during the analysis period of clinical practice. The results obtained were as follows: (a) for small breasts: $E_S < 45$ mm (27 kV; (37.9 ± 6.7) mAs preferably for Mo/Rh); (b) for medium breasts: $45 \leq E_M < 70$ mm (29 kV, (50.7 ± 8.3) mAs, for Rh/Rh); and (c) for large breasts: $E_L \geq 70$ mm (30 kV; (67.4 ± 13.8) mAs for Rh/Rh). The thickness of compressed breasts considered “typical” for each thickness range were $E_{St} = 35$ mm, $E_{Mt} = 55$ mm, and $E_{Lt} = 70$ mm, respectively.

Optimization Study of the Exposure Parameters

Study on the Influence of Image Processing Options in the Value of IQF_{inv}

In the optimization process of the image quality, the influence in the value of IQF_{inv} was evaluated and compared with the image processing options, which were raw image and processed image with *Premium View* and/or *Fine View* filters.

The study of the influence of the image processing options in the value of IQF_{inv} was performed for small breasts configuration of the CDMAM phantom corresponding to Fig. 2. From this configuration, 192 images were obtained. The

Fig. 1 Histogram of the distribution of the sampled compressed breast thicknesses

Fig. 2 Breast sizes and positioning of the CDMAM simulator in mammography

calculated values for IQF_{inv} remained the same for all possible target/filter combinations, current-time product, and voltage applied to the tube.

As shown as an example in Fig. 3, it was observed that the IQF_{inv} values are independent of the options for image processing filters. Therefore, it was decided to use the image processed with both filters (*Premium View* and *Fine View*) instead of the raw image, considering that the processed image is always the one used in the institution's clinical practice, for diagnostic purposes.

The FOM Values as a Function of Exposure Parameters

Figure 4 shows the curves for FOM versus the voltage applied to the X-ray tube (kVp), obtained for typical small breast thickness (E_{St}) and the sets of target/filter combinations: Rh/Rh, Mo/Rh, and Mo/Mo. The fitted data show a Gaussian distribution for all target/filter sets. The criterion used to define the optimal point of the kVp was the point corresponding to the maximum value of the FOM. The Rh/Rh target/filter combination and 30 kVp are the parameters for which the FOM has its highest value.

In STD mode, the system chooses the Mo/Rh exposure parameters with 27 kVp (see black dot in Fig. 4). Taking into account the uncertainty bars associated with each point of the FOM, a significant difference between the FOM values resulting from the exposure in STD mode and the FOM values obtained from the Gaussian peaks for Mo/Rh and Mo/Mo target/filter combinations with 29 kVp is not observed.

Figure 5 shows the curves for FOM versus kVp obtained for typical medium breast thickness (E_{Mt}), for the sets of target/filter combinations: Rh/Rh and Mo/Rh. The fitted data also show a Gaussian distribution for all target/filter sets. The FOM takes its maximum value for the typical medium breast (E_{Mt}) close to the conditions selected in STD mode (Rh/Rh and 30 kVp) considering the error bars.

Figure 6 shows the curves for FOM versus kVp obtained for typical large breast thickness (E_{Lt}), for target/filter Rh/Rh. The best fit for the experimental points was again obtained by a Gaussian curve. The FOM value obtained under the conditions selected for the STD mode (Rh/Rh and 30 kV) is similar to the value obtained using the proposed FOM within the uncertainty range.

Fig. 3 IQF_{inv} values for different image processing modes

For the typical breast thickness, E_{Mt} and E_{Lb} , it is observed that the optimal points obtained from the curve of the proposed FOM are close to the selected by the STD mode, with Rh/Rh. However for the typical small breast thickness, the behavior is different: the maximum value for FOM is significantly distinct than those selected by STD parameters. The optimal FOM point suggests Rh/Rh and 30 kVp instead of Mo/Rh with 27 kVp that is the choice in the STD mode. Once the discrepancy happens for the small breast thickness, it was decided to study the influence of the new optimized parameters for the typical small breast using the anthropomorphic phantom TORMAM.

To this purpose, the study of optimization of current-time products for small breasts and for each optimal kVp point for both target/filter combinations (Rh/Rh and Mo/Mo) was conducted. The results are shown in Table 1

Comparison of the Optimized Exposure Parameters Using TORMAM Phantom for Small Breast Configuration

Table 1 shows the optimum technical parameters chosen from the proposed FOM for small breasts. The comparative studies have been performed with three images obtained from TORMAM phantom, using the technical parameters

Fig. 4 FOM dependence as function of peak kilovoltage, for the possible target/filter combinations. Case of compressed small breasts with 35 mm thickness

Fig. 5 FOM dependence as function of peak kilovoltage, for the possible target/filter combinations. Case of compressed medium breasts with 55 mm thickness

suggested by de optimization studies for Rh/Rh and Mo/Mo target/filter configuration and the STD mode.

Comparative Analysis of SNR and the Number of Gray Levels of the TORMAM Images

The analysis was performed from the signal-to-noise ratio (SNR) of three distinct images obtained with the TORMAM phantom in the small-breast configuration using the parameters values shown in Table 1. JiveX [dv] Personal Edition software was used to obtain the SNR values. A ROI of 30.49 mm² in three separated regions of the image was selected, positioned over the locations with PMMA and without structures. An average SNR value $\langle \text{SNR} \rangle$ was obtained for each one of the three images (Fig. 7).

It is observed that the image obtained with optimized parameters was also the best option when evaluated from the SNR metric. This is a noticeable outcome.

The raw images generated with the technical exposure parameters shown in Table 1 were also analyzed according to the number of gray levels using ImageJ 1.43u software. Figure 8 shows the histograms of the distribution of gray values in the phantom image. The X-axis represents the possible gray values (zero corresponds to white and the number increases towards black) and the Y-axis shows the number of pixels found for each gray value. The bandwidth for each curve was defined as the distance between the X-axis point in which the Y-value starts in the histogram up to the X-axis point where the Y-axis value is approximately 0.1 % of the maximum counting value. Also, this figure shows the difference between the main peaks for the two analyzed images. The

Fig. 6 FOM dependence as function of peak kilovoltage, for the possible target/filter combinations. Case of compressed large breasts with 70 mm thickness

Table 1 Exposure of technical parameters used to obtain images from TORMAM phantom in small breast configuration

Image number	Exposure mode	Target/filter set	Voltage (kVp)	Current-time product (mAs)
1 (optimized)	Manual	Rh/Rh	30	28
2	STD	Mo/Rh	27	35.1
3	Manual	Mo/Mo	29	28

image that exhibits the greatest number of grays levels is a better choice; it is more balanced, among other factors [46–49]. That is, a larger bandwidth of the image histogram results in better image because it presents a greater number of available gray levels. A higher distance between the main peaks indicates a better distinction between the gray levels, which implies greater contrast. As can be seen in Fig. 8, the image obtained with optimized parameters shows the highest number of gray levels (1472) and a higher shift between the main peaks.

Detection of Breast Structures in the Anthropomorphic Phantom

Some authors report studies comparing the performance between an observer and a software for the automated quality assessment of images [50]. Using CDRAD contrast-detail test object, with a similar architecture to CDMAM, these authors showed that the software has proven to be most sensitive to detect smaller low-contrast variations, while the observer showed a better performance in detecting smaller details. They pointed out that the use of an image quality figure such as IQF_{inv} , for absolute comparative studies, should be used carefully. Therefore, for this reason the methodology developed in this study also included a step of parameter evaluation, optimized via IQF_{inv} , using images of an anthropomorphic

phantom whose appraisal was performed by experienced radiologists.

The statistical analysis of the images evaluated by radiologists was based in the image Visualization Indicator and considering each specific structure (filaments, microcalcifications, and masses). Table 2 summarizes the visualization indicator results for each structure, considering the scores of the six radiologists for 18 evaluated images (each image was shown three times to the same radiologist). It shows the mean, standard deviation (SD), and coefficient of variation (CV) for the visualization indicator. The maximum possible score for the visualization indicator for each structure was 18 (6 variations of each structure $\times$ the maximum score = 3). The table also shows the values of minimum and maximum scores for each structure assessed by the radiologists. From these results, the homogeneity between all evaluators through the CV was verified. It can be observed in Table 2 that for the evaluation of filaments, microcalcifications, and masses, image 1 showed the greatest homogeneity (smallest CV). It is observed that the average value of the Visualization Indicator for the optimized image is greater than the Visualization Indicator of the standard image (STD) for all structures (5.6 % to microcalcifications, 4.7 % to filaments, and 2.7 % to masses).

Considering the set of structures (microcalcifications, fibers, and masses), a similar value for the visualization indicator in image 1 (optimized) and image 2 (STD) was obtained. Furthermore, the optimized image showed a higher visibility of microcalcifications. Then, using the set of optimized parameters, the best results for microcalcifications detection and similar results for other structures (filaments and masses) can be achieved. Based on the values obtained for the ICC (all above 0.8), the image evaluations were quite homogeneous when reviewed by the same radiologist. Thus, according to the results of this work, the images obtained with the optimized parameters using the proposed FOM, which includes IQF_{inv} (obtained from the CDMAM software package), also proved to be the best images evaluated by the observers.

Fig. 7 Values for $\langle SNR \rangle$ from TORMAM phantom images in small breast configuration

Conclusions

In this paper, a new FOM is proposed in order to optimize image quality versus dose in digital mammography. The

Fig. 8 Gray level histogram of the studied images from the TORMAM phantom in small breast configuration

results indicated that the use of this methodology allows the improvement of the optimization process of the digital mammogram exposure parameters, taking distinct breast thicknesses into account.

The optimized image from the proposed FOM showed the best signal-to-noise ratio and exhibited the largest gradient in

the number of gray levels. The results of the analysis of these image's metrics allowed us to conclude also that the optimized image for the small breast is better than the image obtained with STD parameters.

Statistical analysis of the radiologists' evaluations indicates that the optimized image allows a better detection of

Table 2 Comparison of the results of the visualization indicator, considering the 18 images evaluated by all six radiologists, for each structure type

Structures/image parameters	Visualization indicator				
	Minimum	Maximum	Average	SD	CV
Filaments					
Rh/Rh, manual, 30 kVp, 28 mAs	8.0	15	12.7	2.2	0.17
Mo/Rh, STD, 27 kVp, 35.1 mAs	6.0	16	12.1	2.9	0.24
Mo/Mo, manual, 29 kVp, 28 mAs	6.0	15	12.3	2.6	0.21
Microcalcifications					
Rh/Rh, manual, 30 kVp, 28 mAs	7.0	13	10.8	1.7	0.16
Mo/Rh, STD, 27 kVp, 35.1 mAs	6.0	13	10.2	2.2	0.22
Mo/Mo, manual, 29 kVp, 28 mAs	6.0	13	10.3	2.1	0.20
Masses					
Rh/Rh, manual, 30 kVp, 28 mAs	18.0	31	25.9	3.5	0.14
Mo/Rh, STD, 27 kVp, 35.1 mAs	18.0	31	25.2	4.0	0.16
Mo/Mo, manual, 29 kVp, 28 mAs	15.0	25	21.1	3.2	0.15
Total					
Rh/Rh, manual, 30 kVp, 28 mAs	33.0	58	49.4	6.8	0.14
Mo/Rh, STD, 27 kVp, 35.1 mAs	30.0	58	47.4	8.1	0.17
Mo/Mo, manual, 29 kVp, 28 mAs	29.0	53	43.7	7.0	0.16

microcalcifications compared with the image obtained by the use of the STD mode, without loss of quality for the identification of fibers and masses.

It is difficult to state that a particular figure of merit is absolutely better than another. In reality, each FOM emphasizes certain aspects of an image [26], which can facilitate detection of specific types of structures. In general, the proposed FOM in this work offers a new alternative tool for the optimization of mammography.

Compared to other figures of merit that have been reported in literature for use in mammography, the FOM proposed in this work is different in several aspects. In other studies, FOM are commonly used as image parameters: signal-to-noise ratio and contrast-to-noise ratio, since this is a FOM that uses the CD as metric, which especially favors the detection of breast microcalcifications. Another particular feature of the proposed FOM is that it allows its application in processed images. This fact constitutes an advantage compared with others FOM that are applied using raw images, once the radiologists always use the processed images to perform the clinical diagnosis.

This paper presents the results obtained with the equipment Senograph GE; however, we believe it is necessary to carry out further work with application of FOM in other types of technologies with different generators and RX detectors. Furthermore, the results of this optimization were applied in the TORMAM phantom with glandularity 50 %. In this regard, it could be relevant to carry out a study on the influence of variation of glandularity on the results of optimization.

Since the proposed FOM favors the detection of microcalcifications, this can facilitate the plan setting of the next steps of the clinical investigation of the patient, such as the need to perform or not the biopsy, and the application of appropriate medical treatment in cases of breast cancer.

The results obtained for small breasts indicate that the proposed FOM can be used as a practical and efficient tool for the optimization of image and dose in digital mammography equipment. This study presents an alternative and reliable way for digital mammography optimization.

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